# FNAL-Homestake Beam Design and Event Rates

## UDiG Workshop, 10/17/08

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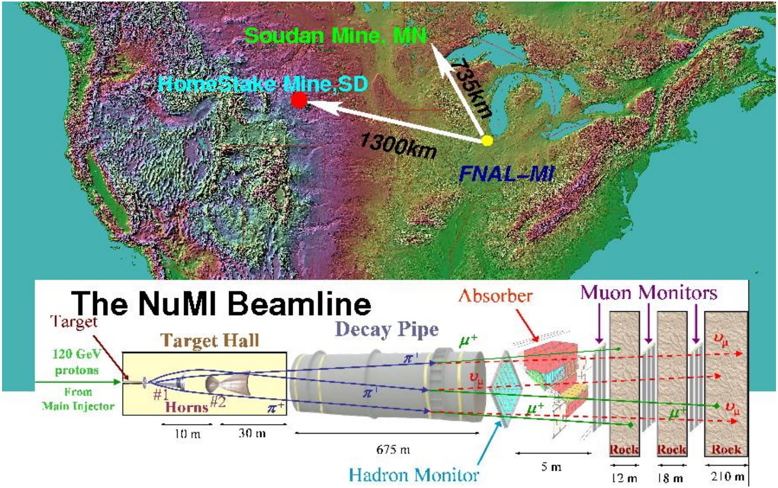
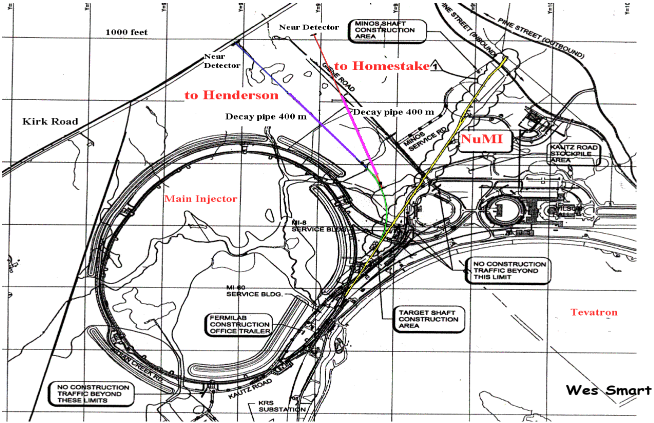
# Outline

# Neutrino Beamlines at FNAL





# Layout of the NuMI/Hstake beam

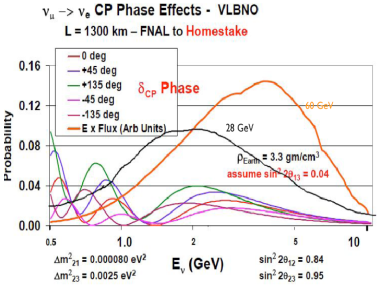



**Current design is to use the NuMI extraction and carrier tunnel down into the good rock near the NuMI target hall, then direct the proton beam down a new tunnel towards Homestake.**

# Requirements of the FNAL/Homestake Beam



*The design specifications of a new WBLE beam based at the Fermilab MI are driven by the physics of $\nu_\mu \rightarrow \nu_e$ oscillations:*




L = 1300 km

**Requirements:**

**-Maximal possible neutrino fluxes to encompass the 1st and 2nd oscillation nodes, with maxima at 2.4 and 0.8 GeV.**

**-High purity $\nu_\mu$ beam with negligible $\nu_e$**

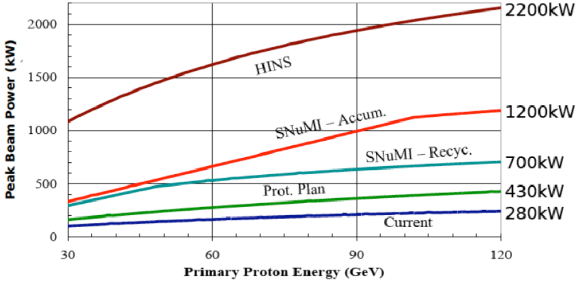
**-Minimize the neutral-current feed-down contamination at lower energy, therefore minimizing the flux of neutrinos with energies greater than 5 GeV where there is no sensitivity to the oscillation parameters is highly desirable.**

# Present/Future proton beam options from FNAL



**SNuMI:** Use the recycler (and anti-proton accumulator?) to store protons from the 8 GeV 15 Hz Booster during the MI cycle then inject to MI $\rightarrow$ increases MI intensity up to $6 \times 10^{13}$ protons $\Rightarrow$ **0.7 (1.2) MW at 120 GeV.**

**HINS a.k.a Project X:** S.C. Linac replaces 8 GeV Booster, MI upgrades $\Rightarrow$ **2.2MW at 120GeV**

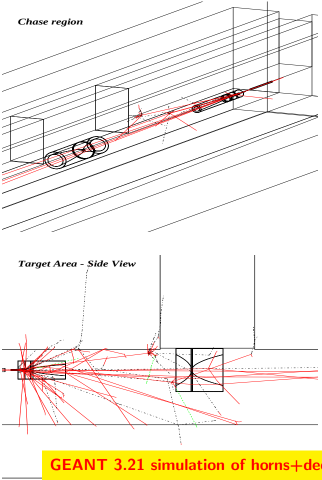



**CHALLENGE: Can we use a 120 GeV beam to produce a low energy wide-band neutrino beam for megaton detectors at Hstake?**

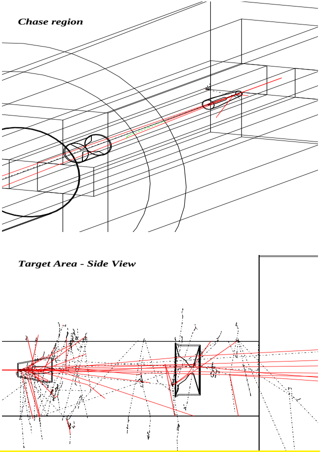
# Example of a DUSEL beam simulation

*Beam to DUSEL: carbon-composite target with a density of 2.1g/cm$^3$ for a MW class beam + 2 wide-band horns based on BNL-AGS E734/E889:*

**NuMI horns/target with 120 GeV p+**




**Wide-band horns/target with 120 GeV p+**

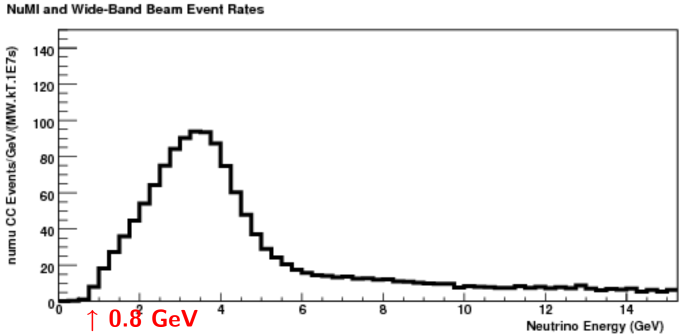



**GEANT 3.21 simulation of horns+decay pipe, with FLUKA '05 for target hadro-production.**

# Designing the right beam



*Getting significant flux at BOTH 2.4 GeV and* $\sim 0.5 - 1.5$ *Gev region is critical to CPV sensitivity (see Mark Dierckxsens talk).*




**The NuMI LE beam at 735 km, with 185kA horn current**

# Designing the right beam

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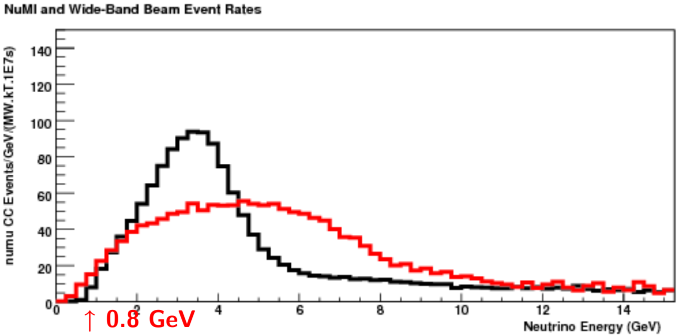
Making Neutrinos at FNAL

NuMI/Hstake Designs

Event rates and sensitivities

Summary and Plans

*Getting significant flux at BOTH 2.4 GeV and $\sim 0.5 - 1.5$ Gev region is critical to CPV sensitivity (see Mark Dierckxsens talk).*

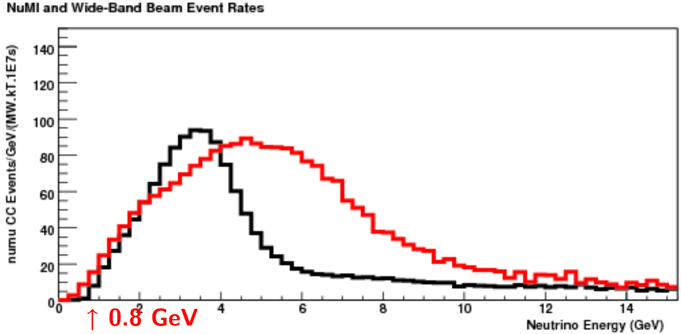



**Replace with BNL wide-band target/horns at 185kA horn current**

# Designing the right beam



*Getting significant flux at BOTH 2.4 GeV and* $\sim 0.5 - 1.5$ *Gev region is critical to CPV sensitivity (see Mark Dierckxsens talk).*




**Increase tunnel diameter from 2 to 4m**

# Designing the right beam



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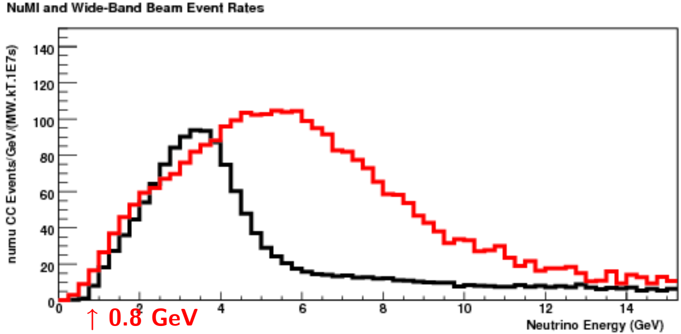


**Increase wide-band horn current to 250kA**

# Designing the right beam



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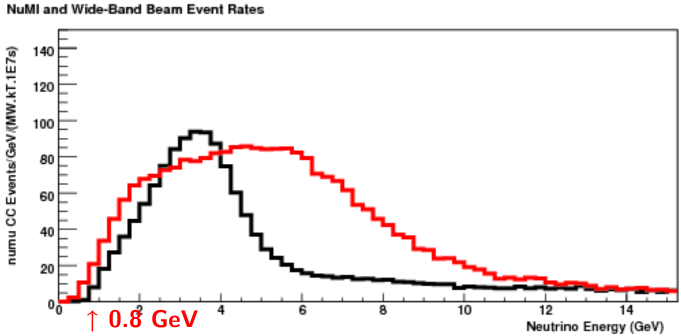


**Decrease tunnel length from 677 to 380m (smaller target chase)**

# Designing the right beam

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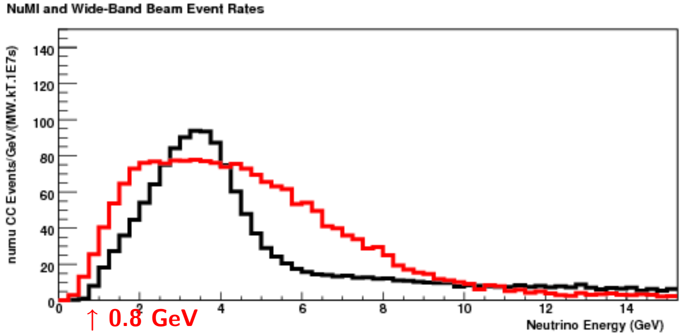
Mary Bishai Brookhaven National Lab



*Getting significant flux at BOTH 2.4 GeV and $\sim 0.5 - 1.5$ Gev region is critical to CPV sensitivity (see Mark Dierckxsens talk).*



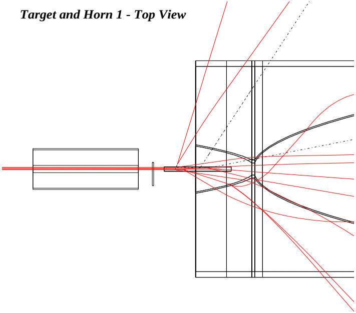

**Decrease proton beam energy from 120 to 60 GeV**

# Latest target/focusing system design

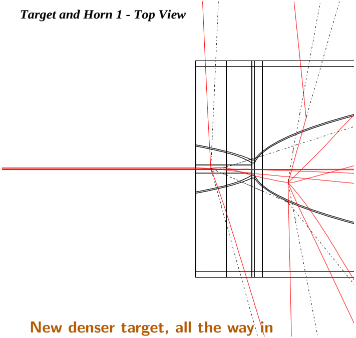


**GOAL: Optimize focusing and decay pipe size for 120 GeV beam using NuMI-like horns**

**Insert CC target (r=6mm,L=80cm,$\rho = 2.1$ g/cm$^3$) into NuMI Horn1, increase current to 250kA:**




Default NuMI target/fin/baffle

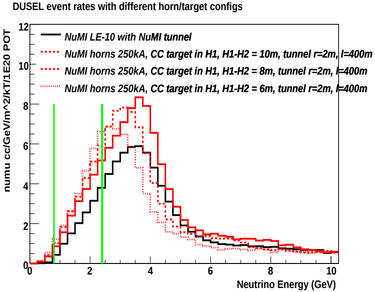


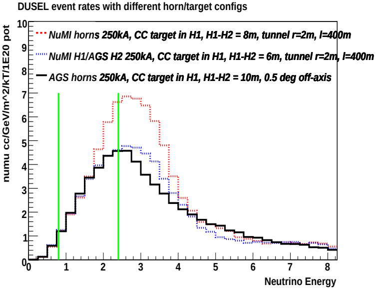

New denser target, all the way in

# Optimizing DUSEL spectra with NuMI horns



*1-Decrease separation between Horn1 and Horn2*
*2-Try different horn combinations of WBLE and NuMI horns*



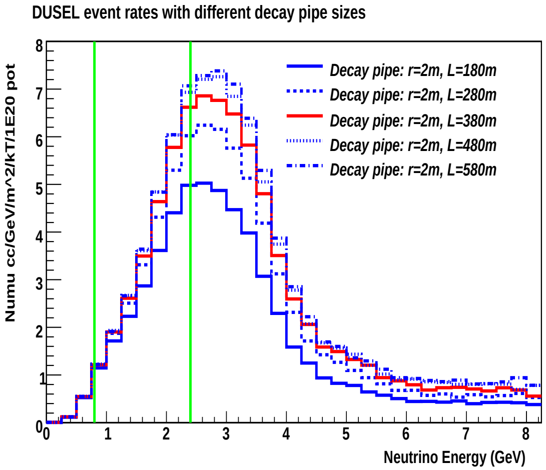




**Using the NuMI horns with different target configuration and the wider decay pipe produces an on-axis flux compatible with a WCe DUSEL detector**

# Optimizing the decay pipe length



*The size of the decay pipe is one of the largest cost-drivers for the beamline - how small a volume can we use?*

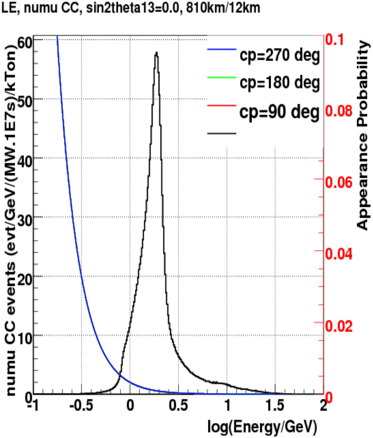


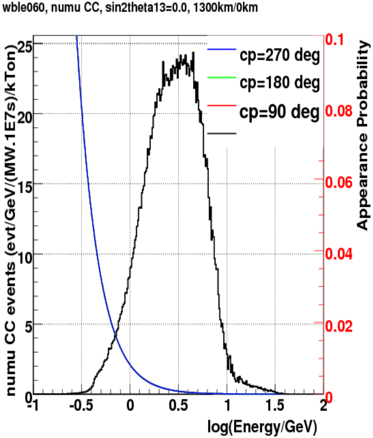

**A decay pipe length of 300-400m is adequate**

# $\nu_e$ Appearance Probabilities

**Normal hierarchy, $\Delta m^2_{32} = 2.5 \times 10^{-3}$ eV$^2$, $\Delta m^2_{12} = 8.6 \times 10^{-5}$ eV$^2$,**

**NuMI off-axis at 810 km** | **WBLE 60 GeV at 1300km**




$\mathbf{P(\nu_\mu \rightarrow \nu_e, \delta_{cp} = 0) = 0.9 \times 10^{-3}}$

$\mathbf{P(\nu_\mu \rightarrow \nu_e, \delta_{cp} = 0) = 1.1 \times 10^{-3}}$

$\mathbf{\sin^2(2\theta_{13}) = 0.000}$

# $\nu_e$ Appearance Probabilities



**Normal hierarchy, $\Delta m^2_{32} = 2.5 \times 10^{-3}$ eV$^2$, $\Delta m^2_{12} = 8.6 \times 10^{-5}$ eV$^2$,**

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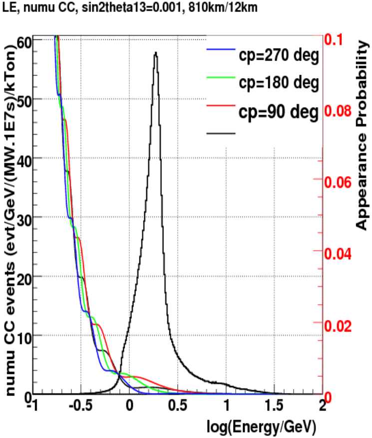
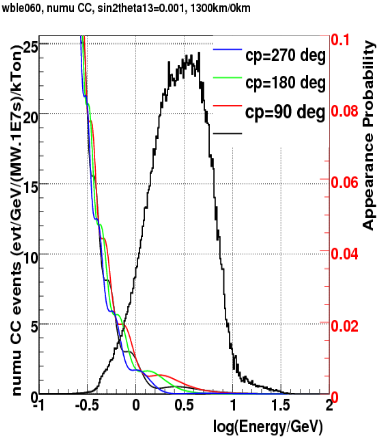



$\mathbf{P(\nu_\mu \rightarrow \nu_e, \delta_{cp} = 0) = 1.3 \times 10^{-3}}$

$\mathbf{P(\nu_\mu \rightarrow \nu_e, \delta_{cp} = 0) = 1.6 \times 10^{-3}}$

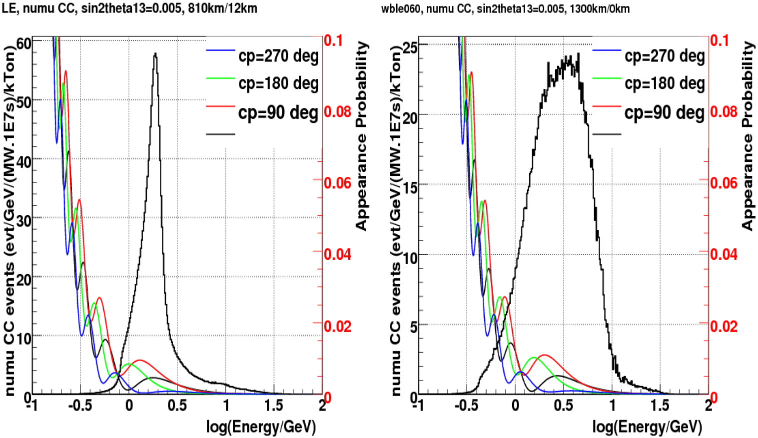
$\mathbf{\sin^2(2\theta_{13}) = 0.001}$

# $\nu_e$ Appearance Probabilities



**Normal hierarchy, $\Delta m^2_{32} = 2.5 \times 10^{-3}$ eV$^2$, $\Delta m^2_{12} = 8.6 \times 10^{-5}$ eV$^2$,**

**NuMI off-axis at 810 km　　WBLE 60 GeV at 1300km**




$P(\nu_\mu \rightarrow \nu_e, \delta_{cp} = 0) = 3.0 \times 10^{-3}$　　$P(\nu_\mu \rightarrow \nu_e, \delta_{cp} = 0) = 3.2 \times 10^{-3}$

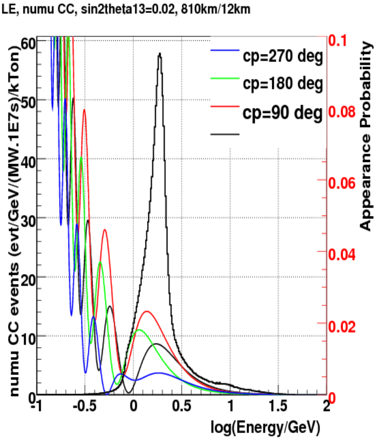
$\sin^2(2\theta_{13}) = 0.005$

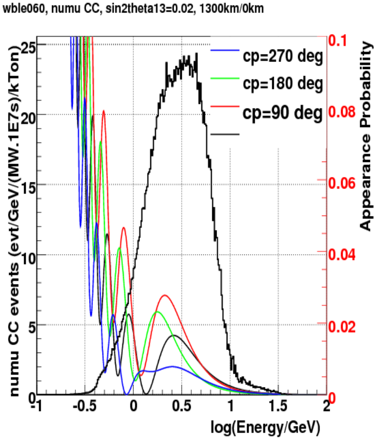
# $\nu_e$ Appearance Probabilities



**Normal hierarchy, $\Delta m^2_{32} = 2.5 \times 10^{-3}$ eV$^2$, $\Delta m^2_{12} = 8.6 \times 10^{-5}$ eV$^2$,**

**NuMI off-axis at 810 km** | **WBLE 60 GeV at 1300km**




$\mathbf{P(\nu_\mu \rightarrow \nu_e, \delta_{cp} = 0) = 8.9 \times 10^{-3}}$

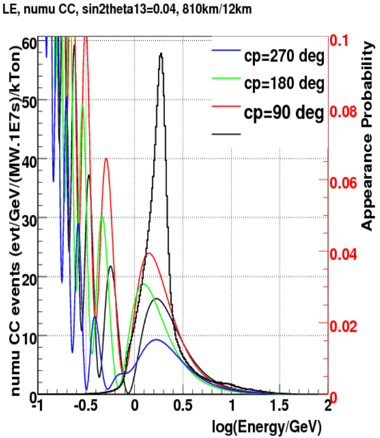
$\mathbf{P(\nu_\mu \rightarrow \nu_e, \delta_{cp} = 0) = 9.1 \times 10^{-3}}$

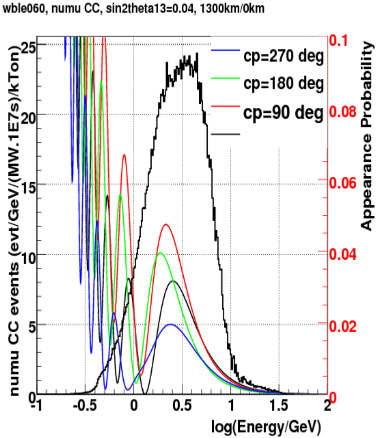
$\mathbf{\sin^2(2\theta_{13}) = 0.02}$

# $\nu_e$ Appearance Probabilities

**Normal hierarchy, $\Delta m^2_{32} = 2.5 \times 10^{-3}$ eV$^2$, $\Delta m^2_{12} = 8.6 \times 10^{-5}$ eV$^2$,**

**NuMI off-axis at 810 km** | **WBLE 60 GeV at 1300km**



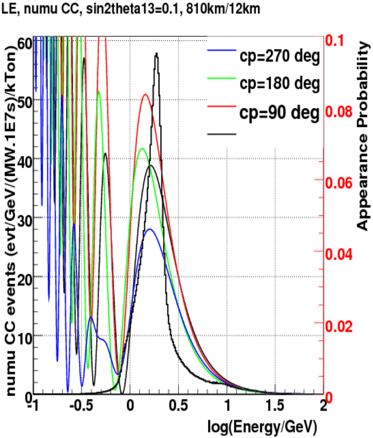

$\mathbf{P(\nu_\mu \rightarrow \nu_e, \delta_{cp} = 0) = 1.7 \times 10^{-2}}$ | $\mathbf{P(\nu_\mu \rightarrow \nu_e, \delta_{cp} = 0) = 1.7 \times 10^{-2}}$

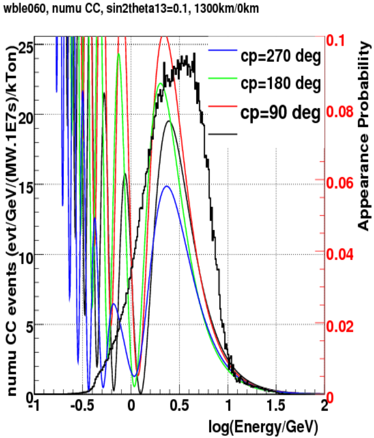
$\sin^2(2\theta_{13}) = 0.04$

# $\nu_e$ Appearance Probabilities

**Normal hierarchy, $\Delta m^2_{32} = 2.5 \times 10^{-3}$ eV$^2$, $\Delta m^2_{12} = 8.6 \times 10^{-5}$ eV$^2$,**

**NuMI off-axis at 810 km** | **WBLE 60 GeV at 1300km**




$P(\nu_\mu \rightarrow \nu_e, \delta_{cp} = 0) = 4.0 \times 10^{-2}$

$P(\nu_\mu \rightarrow \nu_e, \delta_{cp} = 0) = 3.9 \times 10^{-2}$

$\sin^2(2\theta_{13}) = 0.1$

# Raw event rates

**Unoscillated $\nu_\mu$ rates at 1300km:**

**120 GeV on-axis: 20,000 CC/MW.100kT.$10^7$, 9mrad off-axis: 9,000 CC/MW.100 kT.$10^7$s**

**60 GeV on-axis: 15,000 CC/MW.100kT.$10^7$s**

**Oscillated rates at 1300km:**

| | | $\nu_\mu \to \nu_e$ rate | | | | $\bar{\nu}_\mu \to \bar{\nu}_e$ rates | | | |
|---|---|---|---|---|---|---|---|---|---|
| (sign of $\Delta m^2_{31}$) | $\sin^2 2\theta_{13}$ | $\delta_{CP}$ deg. | | | | | | | |
| | | 0° | -90° | 180° | +90° | 0° | -90° | 180° | +90° |
| WBLE beams at 1300km, per 100kT. MW. $10^7$s | | | | | | | | | |
| 120 GeV, 9 mRad off-axis | | Beam $\nu_e$ = 47** | | | | Beam $\bar{\nu}_e$ = 17** | | | |
| (+/-) | 0.0 | 14 | N/A | N/A | N/A | 5.0 | N/A | N/A | N/A |
| (+) | 0.02 | 87 | 134 | 95 | 48 | 20 | 7.2 | 15 | 27 |
| (-) | 0.02 | 39 | 72 | 51 | 19 | 38 | 19 | 33 | 52 |
| 60 GeV, on-axis | | Beam $\nu_e$ = 61** | | | | Beam $\bar{\nu}_e$ = 22** | | | |
| (+) | 0.02 | 138 | 189 | 125 | 74 | 30 | 12 | 19 | 37 |
| (-) | 0.02 | 57 | 108 | 86 | 34 | 46 | 27 | 48 | 67 |

$\Delta m^2_{21,31} = 8.6 \times 10^{-5}, 2.5 \times 10^{-3}$ eV$^2$, $\sin^2 2\theta_{12,23} = 0.86, 1.0$

* = 0-3 GeV ** = 0-5 GeV, 1 MW. $10^7$s = $5.2 \times 10^{20}$ POT at 120 GeV, 1yr = $2 \times 10^7$s

**100kT <u>effective</u> mass is MINIMUM**

# Physics Sensitivities



(see M. Dierckxsens talk yesterday for details...)

*Physics sensitivity with WCe, $3\sigma$ for all $\delta_{cp}$ ($\theta_{13}$, hier)/50% $\delta_{cp}$ (CPV)*

| Beam | Det size (FIDUCIAL) | Exposure $\nu + \bar{\nu}$ | bkgd uncert | $\sin^2 2\theta_{13}$ | sign($\Delta m^2_{31}$) | CPV |
|---|---|---|---|---|---|---|
| NuMI/HStake | 100kT | 700kW 2.6+2.6yrs | 5% | 0.018 | 0.044 | $>$ 0.1 |
| 120 GeV | 100kT | 1MW 3+3yrs | 5% | 0.014 | 0.031 | $>$ 0.1 |
| 9mrad off-axis | 300kT | 1MW 3+3yrs | 5% | 0.008 | 0.017 | 0.025 |
| | 300kT | 1MW 3+3yrs | 10% | 0.009 | 0.018 | 0.036 |
| | 300kT | 2MW 3+3yrs | 5% | 0.005 | 0.012 | 0.012 |
| | 300kT | 2MW 3+3yrs | 10% | 0.006 | 0.013 | 0.015 |

**NB: Flux at 1st oscillation maximum has increased by 25% since these calculations**

# Summary and Plans



- **Very preliminary studies in optimizing the focusing system for the DUSEL beamline using 120 GeV beam have demonstrated:**
  - **NuMI horns without modification + thicker denser target inside NuMI horn 1 can produce an ON-AXIS beam that will work with WCe**
- **Still having trouble getting enough flux at 1GeV (see Mark Dierckxsens talk). Some ideas:**
  - **We can lower the beam energy to $\sim$ 100 GeV without much loss of power.**
  - **Increase horn currents to 350kA - can we run at these currents?**
  - **Small still gains possible with horn/target size and configuration.**
- **Decay pipe lengths between 300-400m are sufficient with radius = 2m. Optimization of shape to control civil construction costs without compromising physics reach is CRITICAL**